

Design and analysis of highly effective pulse tube engine



Taekyung Ki*, Sangkwon Jeong

Cryogenic Engineering Laboratory, Division of Mechanical Engineering, School of Mechanical, Aerospace and System Engineering, Korea Advanced Institute of Science and Technology, Guseong-dong, Yuseong-gu, Daejeon 305-701, Republic of Korea

HIGHLIGHTS

- Configurations of effective pulse tube engine are suggested.
- Performance and efficiency of pulse tube engines are investigated from simulation.
- Carnot efficiencies of pulse tube engines fall in the range of 40 and 55%.

ARTICLE INFO

Article history:

Received 26 April 2012

Accepted 11 January 2013

Available online 24 January 2013

Keywords:

Design

Efficiency

Pulse tube engine

Stirling engine

Thermoacoustic engine

ABSTRACT

Configurations and performances of a pulse tube engine are devised and investigated in this paper. Energy flow concept and mechanical–acoustical analogy enable one to design several different types of pulse tube engine. They are classified as a pulse tube engine equipped with two pistons or one piston and a tandem pulse tube engine. Specially, the pulse tube engine with one piston is basically identical with a well-known thermoacoustic engine. The simulation results in this paper show that the Carnot efficiencies of the pulse tube engines fall in the range of 40 and 55%.

© 2013 Elsevier Ltd. All rights reserved.

1. Introduction

In a pulse tube refrigerator (PTR), a cold part piston of a Stirling refrigerator is to be replaced with a pulse tube and a phase controller. With such an evolutionary discrepancy in mechanical components, the operation of PTR is similar to that of a Stirling refrigerator although the former actually relies on fundamental non-equilibrium characteristic. Without moving parts at the low temperature region, a PTR has great advantages of high reliability, low noise, low vibration, and low cost, which are very attractive to many fields where cryogenic cooling is required [1,2]. Since a Stirling refrigerator operates by a reverse Stirling cycle, it can also work reversely like an engine based on a Stirling cycle. There have been numerous researches about Stirling engines for last few decades. A PTR having a similar mechanism with a Stirling refrigerator also can potentially operate like an engine. A pulse tube engine (PTE) has several engineering advantages that the moving pistons can be located only at ambient temperature region and the technical

demand for the hot-end heat exchanger and the expansion space is less severe than that of a Stirling engine, because the space of a pulse tube can allow more design flexibility. Nevertheless, the research about a pulse tube engine (PTE) [3,4] is rarely done. Yoshida et al. [3] proposed a PTE of the simple structure classified into the standing wave engine group and measured the work flux density distribution over the cross section of the pulse tube. The proposed PTE has the low efficiency but they confirm the PTE normally operates. Zhu and Nogawa [4] introduced a numerical model for the simulation of the pulse tube Stirling machine with warm gas-driven displacer and a displacer rod. They confirmed that the pulse tube engine which has the same structure as PTR could normally operate as an engine by using the numerical model. Here, they only focus on the confirmation of possibility that the pulse tube machine operates as a cryogenic refrigerator and an engine. More research is needed to improve the performance of PTE and understand the mechanism of PTE.

In this paper, we suggest various configurations of PTE and present analytic investigation results on the performance of PTEs. First, we confirm the basic structure of PTE could normally operate by using energy flow concept and suggest various structures of PTE by using analogy. Second, we optimally design the configurations of

* Corresponding author. Fax: +82 42 350 8207.

E-mail addresses: kingcandy@kaist.ac.kr (T. Ki), skjeong@kaist.ac.kr (S. Jeong).

PTEs by the simulation tool. Finally, we confirm that the PTEs could have high efficiencies and the phase relation of working fluid in the PTEs is important. In these processes, it is verified that PTE can be widely used as an engine.

2. Concept of PTE and design of basic configuration

Energy flow concept [5] is used to design a basic configuration of a PTE. In an ideal case, the enthalpy flow of a regenerator is zero

because the ineffectiveness loss at the regenerator is zero. When heat supplied from a hot-end heat exchanger is converted to the enthalpy flow of gas in a pulse tube, an expansion work is generated at the back of the pulse tube and an expansion piston must be located at the back of the pulse tube to recover the energy and produce a useful work. This process is identical to the case of Stirling engine except for the fact that the PTE involves a non-negligible compressible gas column as an expander. A schematic diagram of the basic type PTE is shown in Fig. 1(a). The PTE consists of two

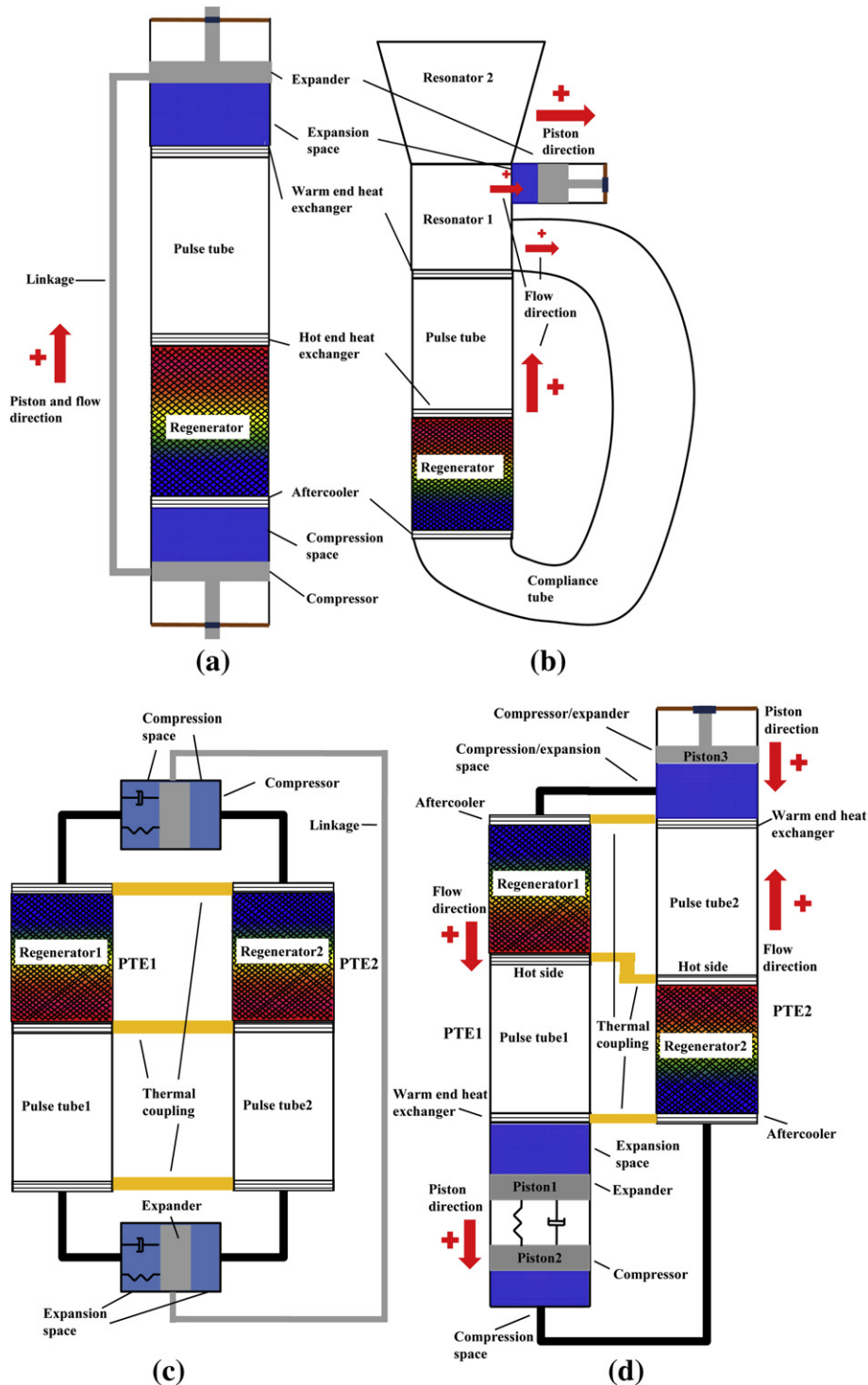


Fig. 1. Configurations of PTEs. (a) PTE with two pistons (basic type PTE). (b) PTE with one piston. (c) Typical tandem PTE. (d) Developed tandem PTE.

pistons located at the compressor and the expander, respectively. An expansion work is generated in the expander and the compressor is run by the compression work supplied from the expansion work. The two pistons are to be connected by an external mechanical linkage (An external mechanical linkage can be replaced with a proper mass, spring, and damper of compressor and expander like a free-piston Stirling engine. Then, the mass, spring damper will be carefully designed to make a proper phase difference between the pistons.). A proper phase difference of motion between two pistons is required to operate like a Stirling cycle. Therefore, an elaborately selected specific kinematic design of mechanical linkage between two pistons is important.

3. Design of different type PTEs

3.1. PTE with one piston

Similar to the case of a PTR, a mechanical system of a piston, a spring, and a damper can be replaced with an acoustic system that is consisted of an inertance tube and a reservoir. The compressor of the basic type PTE, therefore, can be replaced with an acoustic system. Since a part of the expansion work must be transferred to an acoustic power for the compression work, an expander and an acoustic system should be connected. This condition requires the connection between the expansion and the compression spaces and a proper phase difference between a gas flow in the expansion space and a gas flow in the compression space controlled by the acoustic system, simultaneously. Fig. 1(b) shows the configuration of the PTE that can satisfy these requirements. A phase difference between the mass flows in the aftercooler and the expansion space is created by a compliance tube that connects the expansion space to the aftercooler. A resonator is implemented to amplify the pressure amplitude of the PTE and to enable the PTE to operate at a resonant frequency, because the additional volume of a compliance tube reduces the pressure amplitude of the PTE. Additionally, the installations of the compliance tube and the resonator can suppress the viscous loss in a regenerator like a double-inlet line that connects an aftercooler and a warm-end heat exchanger at a double-inlet PTR [6].

3.2. Tandem PTE

The PTE with two pistons (Fig. 1(a)) can be transformed to become a tandem PTE. The possible schematic diagrams of a tandem PTE are shown in Fig. 1(c) and (d). The tandem PTE of Fig. 1(c) simply consists of two identical PTE units, which are operated only by two pistons. The pressure variation and the mass flow rate of the working fluid in PTE1 have opposite phase angle as compared with those of the working fluid in PTE2, and the phase relation between the pressure variation and the mass flow rate of the working fluid is the same in the two identical PTEs. This tandem concept is simple, but the single common expander piston works as a mechanical power-generating device to an external system. Fig. 1(d) shows another tandem PTE. The piston1 and the piston2 work as an expander of PTE1 and a compressor of PTE 2, respectively. The piston3 that is shared in PTE1 and PTE2 works simultaneously as a compressor and an expander. By a spring and a damper, the piston1 and the piston2 are connected with each other. A part of the expansion work generated at the piston1 can be provided to the piston2. If the generated expansion work of PTE1 is larger than the required compression work of PTE2, all of the output works are always positive at the pistons (piston1 and piston3) of the tandem PTE. Therefore, the piston1 and piston3 can be used as different net mechanical power-generating devices to an external system. Relative motions of the pistons in this tandem configuration are important factors for efficient operation.

4. Simulation results of designed PTEs

In order to optimally design the parameters of the PTEs depicted in Fig. 1(a), (b), and (d) and simulate the performance, the SAGE program [7], 1-D numerical code based on thermal and fluid dynamic equations for an engine, a refrigerator, and a spring-mass-damper system, is used and the design process [8] of PTR is modified. The detailed specifications and the performance results of PTEs are precisely presented in Table 1. The simulation of PTE depicted in Fig. 1(c) is not done, because its operating mechanism is similar to Fig. 1(a). All three PTEs in the simulation conditions can normally operate as reasonable engines in the simulation conditions. The Carnot efficiency of PTE with two pistons (Fig. 1(a)) is 41% and the performance is comparable to a Stirling engine. Fig. 2 shows variation of net output according to the phase angle of expander piston in PTE with two pistons. This result means that the phase difference of motion between two pistons directly affects the performance. The piston motion of the compressor is suppose to lead that of the expander by 100° in the optimal condition. Fig. 3 shows the PV diagrams in expansion and compression spaces of PTE with two pistons. The PV diagrams of expansion and compression spaces are clockwise and counterclockwise directions, respectively. The PV diagram area of expansion space is larger than these of compression space. A part of expansion work generated in the expander is transferred to the compressor to operate as an engine. The difference between the PV diagram areas is net output of PTE with two pistons. Fig. 4 shows the phase diagram in PTE with two pistons. The relation between the pressure wave and the mass flow rate is an important factor and there is an optimum phase difference between those. The pressure is delayed by the phase angle of 6° with respect to the mass flow rate. The phase difference is the optimum value to maximize the enthalpy flow in the pulse tube. The optimum value is determined from the relation between the energy conversion from heat energy into acoustic power and the regenerator loss.

The PTE with one piston (Fig. 1(b)) has a relatively high Carnot efficiency of 54% according to the simulation result. Since the configuration of PTE with one piston is more optimally designed than that of PTE with two pistons in the same level of heat condition, the input heat is effectively absorbed in the PTE with one piston and the Carnot efficiency of PTE with one piston is higher than that of PTE with two pistons. The volume of PTE with one piston is larger than that of PTE with two pistons, because the compliance tube and the resonator are bulky. The configuration and system size of the PTE with one piston are virtually same as a thermoacoustic engine [9]. Carnot efficiency of a thermoacoustic engine is approximately 40–50% and the results of previous researches [9,10] are similar with the simulation result of this paper. The PTE, whether it is equipped with one piston or two pistons, has its own advantages. Main decision factors for selecting a specific type of PTR will include the compactness of the system or the reduced number of mechanical component like a piston.

Fig. 5(a) shows the mass flow rates and the piston velocities in the two-piston PTE. Fig. 5(b) shows the mass flow rates in the single-piston PTE. The phase differences of mass flow rates at the boundary between the compression space and the aftercooler and the boundary between the warm end heat exchanger and the expansion space (Fig. 5(a)) and the mass flow rates at the boundary between the compliance tube and the aftercooler and the boundary between the resonator1 and the expansion space (Fig. 5(b)) are approximately 120° and 110° , respectively. It means that the phase relation of the mass flow rates between the boundaries of the expansion and the compression spaces should be in the range of 110° and 120° to operate efficiently. In the same pressure swing condition, therefore, the mass flow rates between the boundaries of

Table 1
Specifications and performance of PTEs.

Configuration	PTE with two pistons	PTE with one piston	Tandem PTE
Regenerator	5 cm (ID ^a), 4.7 cm (L ^a), # 200 stainless steel mesh	5 cm (ID ^a), 3 cm (L ^a), # 400 stainless steel mesh	Regenerator 1 5 cm (ID ^a), 4.2 cm (L ^a), # 200 stainless steel mesh Regenerator 2 5 cm (ID ^a), 6.3 cm (L ^a), # 200 stainless steel mesh
Pulse tube	5 cm (ID ^a), 20 cm (L ^a)	4 cm (ID ^a), 10 cm (L ^a)	Pulse tube 1 5 cm (ID ^a), 18.3 cm (L ^a) Pulse tube 2 5 cm (ID ^a), 21.8 cm (L ^a)
Piston of expander	0.49 kg (mass), 3.5 cm (amplitude), −1.74 rad (phase of cosine function)	14.8 g (mass), 3.5 cm (amplitude)	Piston1 0.32 kg (mass), 3 cm (amplitude), −2 rad (phase of cosine function)
Piston of compressor	0.93 kg (mass), 2.1 cm (amplitude), 0 rad (phase of cosine function)		Piston2 0.17 kg (mass), 1.63 cm (amplitude), −0.1 rad (phase of cosine function)
Compliance tube or piston of expander/compressor		5 cm (ID ^a), 3 m (L ^a)	Piston3 0.35 kg (mass), 3 cm (amplitude), 0.8 rad (phase of cosine function)
Resonator		1. Straight tube 5 cm (ID ^a), 0.2 m (L ^a) 2. Tapered tube 5–8 cm (ID ^a), 3.33 m (L ^a)	
Frequency and charging pressure	3.8 Hz, 6 MPa	67.8 Hz, 4.5 MPa	3.2 Hz, 6 MPa
Input heat and working fluid	1546 W@900 K, helium	1382 W@900 K, helium	1500 W@900 K, helium
Net output and Carnot efficiency	402.6 W, 41%	475 W, 54%	511 W, 53.8%

^a ID and L mean inside diameter and length, respectively.

the expansion and the compression spaces in PTE1 and PTE2 of the tandem PTE (Fig. 1(d)) will be maintained with the phase relation like Fig. 5(a) and (b) to operate efficiently. In Fig. 1(d), the motion of the expander piston (piston1) in PTE1 is different from the motion of the compressor piston (piston2) in PTE2, because these two pistons are connected by a spring and a damper. The piston3, however, is common in PTE1 and PTE2. Therefore, the motion of the common piston (piston3) is created by the simultaneous effect of the mass flow rate in the compression space of PTE1 and the mass flow rate in the expansion space of PTE2. When the required phase

relation of the mass flow rates is attained in each PTE, the tandem PTE can operate properly.

Fig. 5(c) shows the variations of the piston velocity and the mass flow rates in the tandem PTE (Fig. 1(d)). Each variation of the mass flow rate in PTE1 and PTE2 has the same tendency of phase relation from the expansion space to the compression space. The mass flow rate (at the boundary between the compression space and the aftercooler in PTE1 and PTE2) leads the mass flow rate (at the boundary between the warm end heat exchanger and the expansion space in PTE1 and PTE2) by 110°, approximately. The tandem

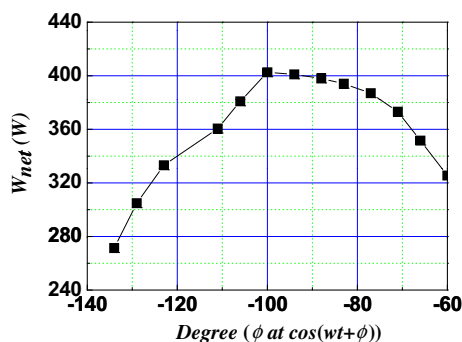


Fig. 2. Net output of PTE with two pistons.

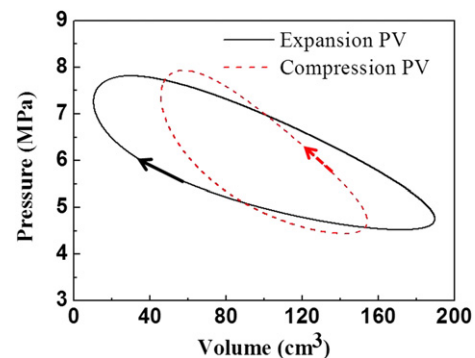


Fig. 3. PV diagram in expansion and compression spaces.

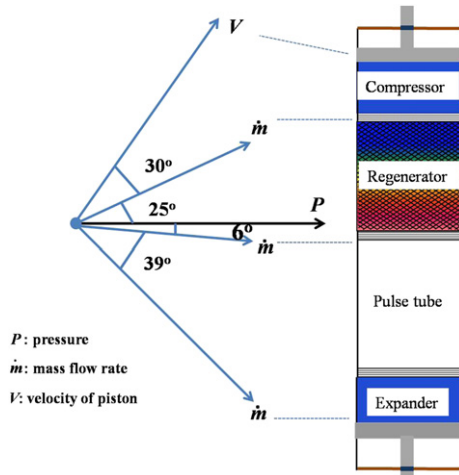


Fig. 4. Phase diagram of pressure wave and mass flow rate in PTE with two pistons.

PTE has a higher Carnot efficiency of 53.8% than the PTE with two pistons. The energy supplied from a heat source is divided into two parts (because of thermal coupling) and the tandem PTE consists of two PTEs in comparison with the PTE with two pistons. In the designed PTE configurations of this paper, therefore, when the input heat supplied in the PTE with two pistons and the tandem PTE is on the same level as shown in Table 1, the energy is effectively absorbed and less dissipated as a low-grade heat in the tandem PTE.

5. Discussion

In the simulation results, the PTEs of three kinds have the different operating conditions, configurations, and performances. The PTE with two pistons and the tandem PTE have lower operating frequencies than that of the PTE with one piston. Each operating frequency is determined by the resonance frequency of system. In order to efficiently generate work in a piston, the piston works in the resonance frequency. In the used simulation program, the resonance frequencies are optimally determined in the ranges of boundary conditions and initial conditions to increase the performance of each PTE. Those conditions are about configurations of components and operating conditions that we considered. So, the PTE with two pistons and the tandem PTE have larger masses (resonance frequency is inversely proportional to mass in vibration system) of pistons and smaller mesh numbers (heat penetration depth is inversely proportional to operating frequency in thermal system) than those of the PTE with one piston. The tandem PTE and the PTE with one piston have higher performance than that of the PTE with two pistons. In the same level heat condition and the ranges of configurations that we consider, the input heat is effectively absorbed in the PTE with one piston and the tandem PTE. Since the PTE with one piston operates with higher frequency than that of the PTE with two pistons, the PTE with one piston effectively absorbs the same level heat. However, the PTE with one piston has bigger size and more complicate structure than the PTE with two pistons. Since the tandem PTE has the two PTEs (PTE1 and PTE2) that only operate by using three pistons, the energy transferred by a heat source is divided into two PTEs and the heat is effectively absorbed in the two PTEs. The PTE with two pistons should operate

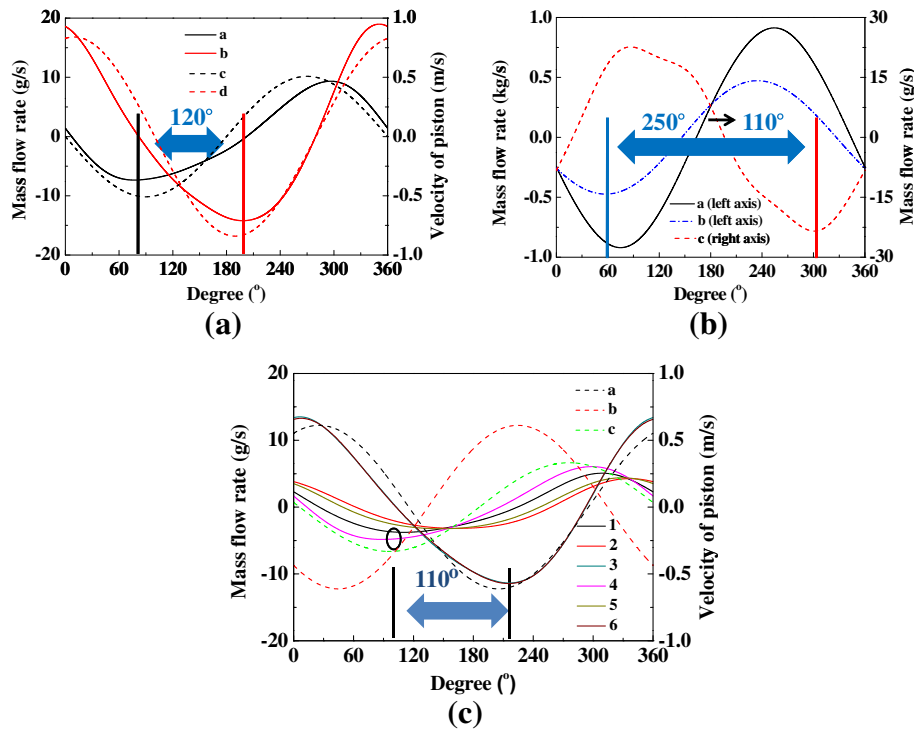


Fig. 5. Variations of mass flow rate and piston velocity in PTEs (The directions of flow and piston motion are presented in Fig. 1.). (a) Mass flow rates and velocities of pistons in PTE with two pistons: a. boundary between compression space and aftercooler; b. boundary between warm end heat exchanger and expansion space; c. piston of compressor; d. piston of expander. (b) Mass flow rates in PTE with one piston: a. boundary between warm end heat exchanger and resonator1; b. boundary between resonator1 and expansion space; c. boundary between compliance tube and aftercooler. (c) Velocities of pistons and mass flow rates in tandem PTE (continuous line-mass flow rate, dotted line-velocity of piston): a. piston1; b. piston2; c. piston3; 1. boundary between compression space and aftercooler in PTE1; 2. hot side of pulse tube1; 3. boundary between warm end heat exchanger and expansion space in PTE1; 4. boundary between compression space and aftercooler in PTE2; 5. hot side of pulse tube2; 6. boundary between warm end heat exchanger and expansion space in PTE2.

in low level heat condition or the configuration should be designed again to effectively convert the input heat into the useful work. Approaches to reduce an irreversibility generated in the basic-type PTE are required.

From the simulation results, we could confirm that the existence of the optimal phase relation between the working fluid and the piston in PTE and PTE using pulse tube like PTR could effectively operate. Therefore, PTE can widely be used as an effective engine.

6. Conclusion

We design and simulate three kinds of PTEs. From the energy flow concept, a PTE with two pistons can be simply designed like a Stirling engine. The compressor of the PTE is replaced with an acoustic system in the subsequent design variation. The PTE with one piston fundamentally resembles a thermoacoustic engine. In consideration of the phase difference between the working fluid motion at the expansion and the compression spaces, a tandem PTE can be also designed. Ideal performance of each PTE is numerically estimated with specific parameters. Carnot efficiencies of the PTEs are calculated in the range of 40 and 50% and, therefore, the feasibility of PTEs is considered high.

Acknowledgements

This research was supported by the Converging Research Center Program funded by the Ministry of Education, Science and Technology (No. 2012K001433).

References

- [1] Y.L. He, J. Huang, C.F. Zhao, Y.W. Liu, First and second law analysis of pulse tube refrigerator, *Appl. Thermal Eng.* 26 (2006) 2301–2307.
- [2] S. Vanapalli, M. Lewis, R. Radebaugh, 120 Hz pulse tube cryocooler for fast cooldown to 50 K, *Appl. Phys. Lett.* 90 (2007) 072504.
- [3] T. Yoshida, T. Yazaki, H. Futaki, K. Hamaguchi, T. Biwa, Work flux density measurements in a pulse tube engine, *Appl. Phys. Lett.* 95 (2009) 044101.
- [4] S. Zhu, M. Nogawa, Pulse tube Stirling machine with warm gas-driven displacer, *Cryogenics* 50 (2010) 320–330.
- [5] P. Kittle, Enthalpy, entropy, and exergy flow losses in pulse tube cryocoolers, *Cryocoolers* 13 (2005) 343–352.
- [6] S. Zhu, P. Wu, Z. Chen, Double inlet pulse tube refrigerators: an important improvement, *Cryogenics* 30 (1990) 514–520.
- [7] D. Gedeon, SAGE: object-oriented software for cryocooler design, in: *Proceedings of 8th International Cryocooler Conference* (1995), pp. 281–292.
- [8] T. Ki, S. Jeong, Step-by-step design methodology for efficient Stirling-type pulse tube refrigerator, *Int. J. Refrigeration* 35 (2012) 1166–1175.
- [9] S. Backhaus, G.W. Swift, A thermoacoustic Stirling heat engine, *Nature (London)* 399 (1999) 355.
- [10] Y. Ueda, T. Biwa, U. Mizutani, T. Yazaki, Acoustic field in a thermoacoustic Stirling engine having a looped tube and resonator, *Appl. Phys. Lett.* 81 (2002) 5252.